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ABSTRACT

This paper summarizes what the author considers to be the best advice available at this time for applying Piaget's theory in the chemistry classroom to understand the difficulties that some students have. The identification of students who are operating at the concrete operational or formal operational level is discussed along with the actual difference between the two levels. Illustrations of the two levels of thought are given within the framework of chemistry activities. The need for concrete operational reasoning and referents in developing new ideas as supported by Piaget's theory is considered in terms of instructional implications. The possibility of using Piaget's theory to identify concepts which are likely to be difficult for concrete operational students to learn is also discussed. (MN)

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PIAGET IN THE CLASSROOM: GUIDELINES FOR APPLICATIONS*

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In "Piaget for Chemists" (1) I tried to explain, in terms of a theory developed by Jean Piaget, why many students do not do well in chemistry.

Since "Piaget for Chemists" appeared, I have had numerous requests for advice on applying Piaget's theory in the classroom. This paper summarizes what I consider to be the best advice available at this time.

Several people have asked me how they can identify students who are operating at the concrete operational or formal operational level. Isn't there a test that can be administered to students so that the sheep can be separated from the goats?

Many people have worked hard to develop a short answer test which can be administered to large groups of students. (2,3,4,5,6,7,8,9,10,11,12) There have been some partial successes. The test developed in France by Longeot (10,11) and translated and used in this country by Sheehan (7) has been used by several people and is undoubtedly of some value but it has limitations. The problem is that when you are trying to classify students as concrete operational or formal operational, you are interested in the reasoning that the student uses. Whereas individual interviews such as those used by Piaget and Inhelder in their work do provide some opportunity to see how the student is thinking, quick-scoring, paper-and-pencil tests provide little opportunity to do this.

* This paper is a condensation of "More Piaget for Chemists: Things That I Wish I Had Told You" presented at the 2YC$_3$ Conference in Kansas City on October 29, 1976 and "Piaget Applied: Suggestions for Inaction" presented at the ACS Convention in New Orleans, March 23, 1977.

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Let me illustrate. The Island Puzzle was described by Karplus several years ago and the following adaptation was used by Tom Sills in a preliminary version of the test he developed at Purdue.*

"Islands A, B, C, and D are four islands in the ocean. People have been traveling among these islands by boat for many years but recently an airline started in business. Carefully read the following statements about the possible plane trips at present.

The trips between islands may be direct or include stops and plane changes on an island. When a trip is possible, it can be made in either direction between the islands. People can go by plane between islands C and D. People cannot go by plane between islands A and B. People can go by plane between islands B and D. Can people go by plane between islands A and C?

A. No, because no statement was made about a plane connection to island A.

B. No, because if you could fly between islands A and C, then you could fly between islands A and B which is not possible.

C. No, because since you can fly between islands C and B, you could fly between islands A and B which is not possible.

D. Not enough information is given to know."

* For further discussion of the Island Puzzle and its value in measuring formal thought, see Blake, et. al. (13).

It can be argued that the logic characteristic of concrete operational thought would lead to choices A and D whereas logic characteristic of formal operational thought would lead to choices B and C. Still, many formal operational thinkers arrive at choice A or D. Subtle interpretations given to the word "between" can lead to various interpretations of the problem. Similar difficulties have been encountered with most short-answer questions designed to measure hypothetico-deductive logic, one of the characteristics of formal thought.

In addition to the problem of formal students giving what are considered to be concrete answers, concrete operational students may give answers that appear to be characteristic of formal thought. For example, the following question appears to involve proportional reasoning, a characteristic of formal thought.

"If 2 apples cost 20 cents,the largest number of apples I can buy with 50 cents is: a) 1 b) 2 c) 3 d) 4 e) 5"

When this item was given to a group of students, many of whom operated at the concrete level, 88% gave the correct answer of 5. Are they using the proportional reasoning characteristic of formal thought? No, they are not. When you interview the students to see how they answered the question, you find that most of them cannot tell you. They are usually unaware of the reasoning employed. If a student does explain his answer, it often goes something like this:

"Well, 2 apples cost (correspond to) 20¢, then 1 apple costs (corresponds to) 10¢, and 5 apples cost (correspond to) 50¢." The reasoning involves seriation and correspondence, the logic of concrete operational thought. If the problem is changed to read, "If 2 apples cost 23¢, how many apples can be bought for 57¢?" most concrete operational students are unable to solve the problem because the seriation and correspondence is less obvious.

An exception would be found in cases where the concrete operational student recalls an algorithm for problems of this kind and applies it without reasoning of any kind.

Apart from my reservations about the validity of group tests of intellectual development, I worry about why chemistry teachers want to identify concrete students at the beginning of the term. If the purpose is placement of students in "slow" or "fast" classes, one should consider factors such as reading ability, existing knowledge of chemical facts, and knowledge of mathematics skills in addition to intellectual development. I suspect that measures such as SAT and the Toledo Chemistry Exam are just as useful for screening purposes as a test of intellectural development.

Perhaps people want to identify students at the concrete operational level so that they can help them. Fine, but a formal test may not be the most efficient way to do this. I make no attempt to classify students as concrete or formal but do try to identify instances of concrete operational thought through informal discussion. When I find that students have difficulty with problems involving proportional reasoning, I go to them during lab or some other convenient time and ask them to tell me how they went about solving the problem. I may give them another problem or two and ask them to talk out loud as they try to solve the problem. Knowing the characteristic reasoning that I am looking for, I believe that I soon get a fairly good reading of the student's ability to use proportional reasoning. I emphasize that this gives me a reading on their ability to do proportional reasoning because there are other aspects of formal reasoning that they may use. From the point of view of the classroom teacher, I am not sure that a gross classification of students as formal or concrete

is what we need. Rather, we need to know if they are comfortable with hypothetico-deductive reasoning (what we normally call "scientific reasoning"), if they habitually think in terms of all possibilities, if they systematically examine all possibilities, they they see the logical necessity of "all other things being equal," if they use proportional reasoning, and so forth. Informal contact in the laboratory, laboratory reports, responses to essay questions, homework problems, and informal class discussions provide ample opportunity to gain clues concerning the student's reasoning. I would emphasize, however, that one needs to be familiar with the characteristics of formal and concrete operational thought and give some attention to the reasoning that students seem to be using in arriving at their responses rather than just saying, "Look what that stupid kid said! How can he be so dumb!"

Let me now move to another point that concerns me. I think that many chemists who have developed a recent interest in Piaget have incorrect or incomplete notions about what is meant by concrete operational thought. For example, I recently talked to a chemist who seemed to equate concrete operational thought with those who do things well with their hands but not with their heads. This represents a gross misunderstanding of the idea. Piaget is talking about <u>intellectual</u> development, not psychomotor development. A concrete operational student may or may not be good with his hands. The distinction is in the <u>reasoning</u> that the student uses and their ability to go beyond actual experience to reason in terms of what has not been experienced.

This latter point was illustrated rather nicely by a comment made by Jane Copes in describing questions that she uses to see how students are

thinking. (14) One question involves a turtle that can fly a certain distance in one time and a rabbit that can fly a different distance in another time; students being asked to tell which flys faster or, if they cannot solve the problem, to explain why. Some students respond that the problem cannot be solved because turtles and rabbits cannot fly. Such a response represents a rather profound inability to divorce oneself from experience and operate in the realm of possibility. Most college students that I work with are beyond this point but it does illustrate the problem.

In discussing an experiment in which students add zinc to a fixed amount of hydrochloric acid and collect the zinc chloride produced, concrete operational students may have difficulty in seeing what would happen if they had added more and more zinc to the fixed amount of HCl or added more and more HCl to a fixed amount of zinc. They need to see it happen -- or at least see the results obtained when other students in the class do the experiment under these hypothesized conditions. Formal operational students more easily divorce themselves from the world of "what I actually saw happen" and operate in the world of "if I did this, what effect would it have on what I saw happen."

I have already mentioned that the logic commonly used by concrete operational students is one of seriation and correspondence. This reasoning is illustrated by an approach used by students in an experiment on linear expansion as a function of temperature. The apparatus had a rod laying on a needle with a cardboard disk attached. As the rod expanded, it rolled the needle and caused the cardboard disk to rotate. A rotation of 360 degrees would correspond to a linear expansion of the rod equivalent

to twice the circumference of the needle. In the experiment, typical expansion caused a rotation of 5 degrees and the problem was to find the change in length of the rod. Many students proceeded as follows:

" 360° corresponds to .20 cm (twice the circumference of the needle)

180° corresponds to .10 cm

90° corresponds to .05 cm

45° corresponds to .025 cm

22.5° corresponds to .0125 cm

11.25° corresponds to .00625 cm

5.625° corresponds to .003125 cm

so the rod expanded a little less than .003125 cm. I would say about .003."

Here the student obtained a series of corresponding values by successive division by 2 and arrived at an answer that was perfectly satisfactory to them. The answer that they got was close enough. Indeed, I expect that in virtually any everyday application of proportional reasoning, this procedure would provide an answer that is close enough. However, the strategy is certainly not as universally applicable as the proportional one that we would use to arrive at the answer of 2.8×10^{-3} cm.

A formal operational student might solve this problem in exactly the same way; particularly if the experience is entirely new to the student.* There are two reasons for this; one is that we tend to use reasoning that we have used successfully in the past and the other is that we always need to describe and order experience (concrete reasoning) before we explain experience (formal reasoning).

* For further discussion on this point see Piaget (15).

To illustrate, consider the basketball player who has just learned to shoot left-handed crip shots. In the beginning it is awkward and uncomfortable. He can do it but it is easier to shoot right-handed. He will often revert to shooting right-handed crip shots when a left-handed shot is more appropriate. In a similar fashion, when a student begins to use formal reasoning, it is awkward. Under stress, the student is likely to revert to concrete reasoning which the student has practiced repeatedly, even in cases where formal reasoning is more appropriate.

When the student is plowing unfamiliar ground, as students were in the linear expansion experiment, it is always necessary to describe and order experience before explaining it or manipulating the information obtained from that experience in a formal way. The seriation and correspondence strategy may be used by a student to get a clear idea of how the expansion of the rod is related to the rotation of the cardboard disk. It may even be a necessary step before the student can use the proportional reasoning that we would use to solve the problem.

The difference, then, between the formal student and the concrete student is that after describing and ordering the experience using concrete operational thought, the formal student will be able to understand the strategy for solving the problem which employs proportional reasoning when it is pointed out. He will probably adopt this formal strategy for solving similar problems because of its obvious advantages. The concrete operational student will <u>not</u> see the proportional reasoning inherent in the formal strategy and will either avoid using it because it doesn't make sense or will memorize the algorithm which the instructor <u>insists</u> that he learn, and apply (or misapply) the algorithm blindly.

I have already said that formal operational students see the logical necessity of "all other things being equal"; i.e., they control variables in an experiment. Concrete operational students generally do not do this. Some people seem to be confused about what this means in practice. Let me clarify, using more anecdotes.

I recently taught a class for elementary school teachers in which they were asked to design and carry out a simple experiment. One of the students -- one that I have reason to believe was formal operational but rather ignorant about science -- decided to investigate the question of why hot water freezes faster than cold water. (It really does, you know, if conditions are wrong.) He placed 500 ml of tap water in one plastic container and 500 ml of boiling water in an identical container and placed them in the freezing compartment of the refrigerator, going back periodically to see when the water froze. He found that the hot water did freeze sooner than the cold water. He also observed that the level of the water in the container of "hot" water was lower than the level in the container of "cold" water but didn't know what to make of the observation. Eventually, it became obvious that he had not controlled some variables. Does this mean that he was not operating at the formal operational level? I don't think so. He saw the logical necessity of "all other things being equal" and did control all variables he knew were important, but he was ignorant of the fact that the density of water is a function of temperature, that evaporation results in a considerable loss of heat, and several other salient facts. Once he was aware of these variables, he knew that he had to control them and proceeded to do so. Even though he was capable of formal thought, he did not originally design a controlled experiment. Experienced scientists are just as guilty.

In contrast, another student -- one that I believe operated at the concrete level -- decided to investigate a burning candle. He placed a candle under a jar and measured the time that it burned. He then relit the candle and placed it under jars of different sizes, again measuring the time the candle burned. Important variables were apparently controlled and the student seemed to be conscious of the need to use the same candle, place the jar over the candle in the same way, and so forth. Then does the fact that the student controlled variables indicate that he was using formal operational thought? Not necessarily. Concrete operational students are likely to control variables if the number of variables are few (say one or two) and if previous experience has produced evidence that the variable matters. However, they are likely to focus on one variable that they believe to have an effect while they ignore other variables that they believe will have an effect. This student, for example, indicated in our conversations that he thought that the height of the candle might affect the time that it burned and that the kind of wick in the candle might matter and that the thickness of the candle could be important. He then proceeded to test the possibility that the length of the candle was an important variable by observing the burning of a short candle and a long candle. But it happened that the available short candle was a fat one used in a warmer for a tea pot and the long candle was a birthday candle. As he focused attention on the variable of interest, he ignored other variables that he knew could be important. The logical necessity of "all other things being equal" was not apparent in any meaningful way.

Further evidence of this student's failure to use formal reasoning was evident in his conclusion that "the candle burns longer in the large jar than in the small jar because there is more oxygen in the large jar." The propensity of students to give inferences as conclusions is, in my judgment, due to their inability to examine alternative explanations. Based on their past experience (in this case, something the student had been told) they arrive at answers that seem plausible and conclude that this must be the answer. Once such students arrive at an explanation - often by considering only part of the data - they are reluctant to abandon it and consider other possibilities. They have a solution that is consistent with what they know. It constitutes a kind of reality which they are reluctant to abandon for an exploration of the unreal world of possibilities. Even when someone suggests other possibilities, they are likely to respond as this student did, "But it is because the candle burns up the oxygen that it goes out. I don't see the point of your saying that I didn't observe that oxygen was being consumed in my experiment."

Some people seem to believe that once a student has reached the stage of formal operational thought that there is no problem in using abstract discussions of new ideas without concrete experiences such as demonstrations, illustrations, diagrams, and laboratory experiments. Physical chemists are notoriously bad at this. They go merrily on their way explaining thermodynamics, equilibrium, and chemical bonding with complex equations and ideal systems that exist only in one's imagination. Since advanced chemistry students are almost certain to be capable of formal thought, they really see no problem with this. There is.

Piaget argues that everyone reverts to concrete operational or pre-operational thought whenever they encounter a new area. Before one can reason with hypotheses and deductions based on experience, there must be a sound descriptive base which has been put in order.* All of us have seen evidence of this need for concrete referents in order to provide meaning to formal, abstract discussions. How many times have you listened to someone explain a new idea, been confused, and asked, "Can you give me an example?" After you see the application of the idea in one or two concrete instances, you are able to proceed to theoretical discussions but you need the concrete experience before the theory takes on meaning.

Because we are at the point that concrete experience in chemistry is superfluous, we tend to forget that it was not always so and in our rush to "cover the material", we omit the very kind of experiences that can make our subject meaningful to beginning students.

I have taken two courses in chemical thermodynamics during my education. I made suitable grades in both but I did it by memorizing a lot of meaningless equations and algorithms which I applied blindly to a large number of problems without ever seeing any relationship between these problems and real chemical systems. Although all of my physical chemistry colleagues seem to disagree, I don't think that this was necessary. I believe that, had they taken the time and energy to develop some suitable demonstrations or showed films of actual thermodynamic experiments and developed their idealized models in that context, I might have understood what they were trying to tell me. As it is, I still don't understand all that I know about thermodynamics!

* For those who argue for a return to descriptive chemistry in beginning courses, support can be found in Piaget's theory. However, it would help their case if they understood why the descriptive material is needed and organized the material accordingly.

Let me make one additional point about the value of using concrete operational reasoning and concrete referents in developing new ideas. The point is that, by doing so, we may be able to get concrete operational students to believe that a formal procedure is correct even though they do not understand why it is correct. This, in itself, gives more meaning to what we try to teach.

Do any of you have students who do not know what we mean by area or volume? I do and think that I know why. It is because area and volume are generally taught as formal algorithms, assuming that the student already understands what the algorithm produces and why. Students in math class are taught that the area of a rectangle is length times width and that the answer is in square units. Now I contend that it is not immediately obvious that multiplying one length by another length will tell you the number of squares that are required to cover a surface. In fact, it is not even obvious that when one writes 100 ft^2 as the area of a floor that the meaning is that it would take 100 squares measuring 1 foot on a side to cover the surface of the floor. Some students never see this. In the class that I taught for elementary teachers, 3 out of 4 thought that when they used the formula, A = L x W, to get area they were finding out something about the distance around the surface. I think that this class was atypical since I have not observed that much confusion in other classes but the problem certainly exists.

Area can be taught in a purely concrete manner. Using graph paper or square tiles that students can lay on a surface, the concept can be presented as the number of squares that are needed to cover the surface. Students can count the tiles or squares on the graph paper to see how many squares are required. They can then be shown that the counting can be done

through a shorthand procedure summarized by the formula, A = L x W. They can rearrange the tiles into different rectangular shapes and see what the formula always works. Even if they are unable to see why the formula produces the same result as counting, they can come to believe that it does. They can then accept the formula as a useful algorithm -- which is all that it is -- and know what the product actually represents. Similar arguments pertain to the concept of volume.

My second example is closer to the hearts of chemists. In discussing equilibrium calculations you are faced with the problem of determining the concentration of various species in a 0.1 M solution of acetic acid or other weak electrolyte. The typical procedure goes something like this:

Let x represent the amount of electrolyte that dissociates. Then the concentration of undissociated molecules will be 0.1-x and we can write the following expression:

$$k = \frac{x^2}{0.1-x}$$

We can then solve the expression for x if we know the value for k (and we always do or we wouldn't be working the problem). So far we have only applied an algorithm that has been memorized and there is no difficulty, but at this point we want to take a shortcut. (Chemists are notoriously lazy and avoid all unnecessary effort). We say something like, "Since x will be small compared to 0.1, we can ignore it and solve the equation for x by taking the square root." Can any beginning student see why this is true? I contend that it is not obvious and that it cannot be <u>made</u> obvious to any student who does not have a high degree of mathematical sophistication and who does not operate comfortably at the formal operational level.

There is a concrete strategy that can be used to convince the student that the approximation is legitimate in most cases and even lead the student to predict when he had better not rely on the approximation. What I do is have students do a series of calculations in class. (With pocket calculators, it can be done rather quickly.) One group of students does the calculation using the quadratic formula while another group does the same calculation using the suggested approximation. They get the same result. We then repeat the process using initial concentrations of .01 M, .001M, and so forth. They then see that the approximation is rather good until the initial concentration approaches the value of the equilibrium constant. Students do not see <u>why</u> the approximation works using this procedure but they do gain faith that it is legitmate and are confident in using it. I am sure that there are other areas in which such concrete strategies could be used to provide students with more confidence and understanding of what we are trying to teach.

I have tried to stress the importance of using concrete referents as an experiential base to bring meaning to abstract ideas. I now want to caution you not to assume that <u>any</u> concrete experience will be helpful.

Gerald Kulm, mathematics educator at Purdue, recently completed a study that I find interesting and significant. (16) Kulm teaches a math course for elementary education majors in which many students operate at the concrete operational level. Kulm is interested in math labs because they provide concrete experience which might make the abstract ideas of mathematics more meaningful. He hypothesized that laboratory activities would probably be very helpful to concrete operational students who are more dependent on concrete experience for understanding, but that these

laboratory experiences might be a waste of time for formal operational students who, supposedly, would be better prepared to handle the abstract presentation given in lecture. Certainly this is a reasonable hypothesis based on our understanding of intellectual development as described by Piaget.

Kulm classified his students as concrete or formal and then assigned half of each group to either a laboratory class or a lecture class.

Kulm's research hypothesis was that the concrete operational students in the laboratory program would score higher on an end-of-unit examination than the concrete operational students in the lecture approach. The opposite was hypthesized for the formal operational students; i.e., that those in the lecture section would score higher than those in the laboratory section. It didn't turn out that way. As a matter of fact, the results were just the opposite as shown by Table 1. The formal operational students in the laboratory section did better than those in the lecture section and the concrete operational students in the lecture section did better than those in the laboratory section.

I think this result is important if taken only at face value. It provides ample reason to be cautious about premature extrapolation from Piaget's theory to classroom practice. The result is even more interesting when one tries to figure out what might account for the unexpected result.

An examination of the laboratory materials used in Kulm's study gives some indication of why he got his unexpected results. Appendix A shows the first laboratory activity used in Unit II and Appendix B shows the unit test.

Unit II was on numeration systems and dealt with the meaning of place value through activities which required students to express quantitties in numerals to bases other than the standard base of 10. As can be seen from the exercise shown in Appendix A, the laboratory activity involved the use of physical systems as analogs to the system of numeration under consideration. In the example shown, Dienes blocks were used to represent a base 6 system of numeration.*

Kulm describes his lecture activities as "a standard lecture-textbook presentation" and it included activities somewhat like those implied by the unit test shown in Appendix B.

An examination of Table 1 indicates that the laboratory activities may have helped the formal operational students but not the concrete operational students. Why? The answer is that the laboratory activity is valuable only if the student sees a relationship between the physical activity and the numeration system that it is intended to represent. In order to see such relationships, the student must be able to abstract from the physical activity the form of the logic that is inherent in that system and transfer that to the numerical representation of the system. This kind of mental activity is characteristic of formal operational thought but not concrete operational thought.

It is quite likely that the concrete students in the lab saw two activities; one was an activity with wooden blocks, the other was an acitivity with numbers. They probably saw them as unrelated. Consequently, the laboratory activity contributed little to their understanding of the

* The blocks consist of a "unit" which measure 1 cm x 1 cm x 1 cm, a "long" which measures 1 cm x 1 cm x 6 cm, a "flat" which measure 1 cm x 6 cm x 6 cm, and a "block" which measures 6 cm x 6 cm x 6 cm. These correspond respectively to 6^0, 6^1, 6^2, and 6^3.

ideas being taught. The formal students were able to see this relationship between numerical and physical representation, however, and the concrete referent helped them understand the idea of place value which is at the root of the activity.

The difference in achievement in the lecture section is more difficult to explain. The most plausible explanation is the one offered by Kulm. He suggests that the formal students may have been bored by the lecture approach which was basically algorithmic. They may not have practiced the homework assignments as much as the concrete students because they already understood the principle, and when they came to the test, they made more computational errors.

The point that I wish to make in regard to this study is that we cannot assume that a laboratory activity requires no more than concrete operational thought or that a particular physical experience will help a student who operates at the concrete operational level. Providing students with "concrete experience" will have no value if formal operational thought is needed in order to make sense out of the experience.

My interpretation of Kulm's experimental result grows out of experience in teaching science to concrete operational students. As a teacher I have frequently been frustrated by my efforts to make some principle or skill meaningful through use of analogies. They frequently don't work.

I must be careful here to make a distinction between alaogies which are of little value in teaching concrete operational students and illustrations which have considerable value.

If one wants to teach the principle that compounds called indicators have different colors in acid and base solutions, an <u>illustration</u> is easily given. One simply adds an indicator to an acid and a base and perhaps

pours the solutions back and forth to show the color change. There is no problem here. We are dealing with direct observation and the observation is directly related to the idea being taught.

We face a different situation when we want to teach the difference in a weak acid and a strong acid. The key idea here is that some acids are completely dissociated while others are not. There is no way to illustrate dissociation; we cannot magnify solutions of acetic acid and hydrochloric acid and invite students to count the number of molecules that are still intact. The best that we can do is show some physical model or hypothetical picture of the system and suggest that reality is analogous to the model. We have not illustrated what happens; we have provided an analogy to what happens. In this instance, the analogy may be sufficiently close to reality that concrete operational students accept the analogy as an illustration -- that is, as a picture of the real system. If so, the analogy may be of some help but other analogies require far more extrapolation and seem to be of no value whatsoever.

The CHEM Study film on Molecular Spectroscopy provides a beautiful illustration of constructive and distructive interference when some oscilating energy source interacts with molecular models connected by loose springs. It is clear from the film that at certain frequencies, the physical model absorbs vibrational energy. As the frequency of the energy source increases, the vibration of the model ceases until some other natural mode of vibration for the model is reached, at which point the model again vibrates. It is a beautiful illustration of the principle that energy from some oscillating source will be absorbed by a physical system when the frequency of oscillation of the source is the same as the natural frequency of vibration of the physical system.

At this point, the illustration observed in the CHEM Study film turns into an analogy because the whole point of the illustration is to provide a physical analogue of molecules interacting with light. The purpose of the film is to "explain" why certain molecules absorb light at one frequency while other molecules absorb light at another frequency; i.e., to explain the principle of molecular spectroscopy. I am convinced that this analogy -- i.e., the use of a physical system to model the hypothesized behavior of molecules interacting with light -- is very helpful to students who are at formal operational level. They see the form of the logic used in explaining the behavior of the physical system and they can apply this same logical form to the imaginary world of molecules. Not so, I believe, for concrete operational students. They see that the energy is absorbed by the models in the physical system all right but they are unable to abstract from that illustration the form of the logic inherent in it and then apply that same logic to some imaginary system far beyond their experience.

In trying to get students to understand how a double pan balance operates, I have had students explore a meter stick balance and then used it as an analog of the double pan balance. Typical concrete operational students see no relationship. In teaching students to solve stoichiometric problems such as, "One mole of sodium weights 23 g. How many moles of sodium weight 254 g?" I often begin with an analogous problem closer to their experience; e.g., "One dozen eggs cost 82¢. How many dozen eggs cost $5.42?" Students often see no connection between the problems.

The most elaborate analogy that I have used is one in which I used nuts and bolts to represent atoms, calculated the relative weights of these "model atoms", used them to make "molecules", and had students

calculate the empirical formula for samples of such "compounds" as a prelude to the same kind of activity with real compounds. Most students saw no relationship between the nuts and bolts and atoms and molecules.

I am not ready to say that concrete analogs for abstract mathematical relationships or abstract models of chemical systems cannot be used effectively to help concrete operational students but I am ready to say that I do not know how to do that consistently and I don't know anybody else who knows how to do it consistently. Until we learn how to do it, people who assume that any concrete experience will help concrete operational students are in for a rude awakening.

All of us know that students don't have trouble with all of the ideas that we teach in chemistry. However, I am not sure that we have given sufficient attention to the ideas that do cause problems and the reasons that they cause problems. It seems to me that we need some kind of taxonomy of chemical concepts that allows us to predict in advance that a student at the concrete operational level is likely to encounter difficulty. I have begun working on such a taxonomy and would like to share some of the ideas that seem to be useful at this time (17).

So far we have delineated three classes of concepts, those that have perceptible examples and perceptible attributes, those that have perceptible examples but no perceptible attributes, and those that have neither perceptible examples nor perceptible attributes. Concepts that have perceptible examples and perceptible attributes may be thought of as "concrete concepts" because they are easily perceived. Solid and liquid are such concepts. One has no difficulty showing numerous examples of solids or liquids. The examples are clearly perceptible. In similar fashion, one can demonstrate that solids hold their shape whereas liquids do not -- the primary defining attribute of the concepts. Thus, the

attributes of the concept are also perceptible. Such concepts are easily learned by direct experience using reasoning patterns characteristic of concrete operational thought.

Concepts such as element and compound present different problems. Although one has no trouble showing examples of elements or compounds -- i.e., the examples are perceptible -- one is hard put to show what it is about a substance that makes it an element or a compound i.e., the attributes of the concept are not perceptible. Concepts such as atom and molecule go one step further. In this case both the examples and the attributes are imperceptible.

Concepts that have imperceptible examples, imperceptible attributes, or both, might be regarded as formal concepts. Such concepts cannot be learned through direct, concrete experience. It is quite likely that they cannot be totally understood without some formal operational reasoning.

We have begun to look more carefully at these hypotheses (18). One of my doctoral students, Luis Cantu, and I developed six lessons over concepts that ranged from very concrete to very formal. These lesson were then taught to a group of high school students who had been classified as concrete operational or formal operational on the basis of their performance on the Longeot test. We hypothesized that there would be no difference in what was learned by the formal and concrete operational students when they studied concrete concepts but there would be a significant difference when they studied formal concepts.

The mean score for the concrete and formal students on tests over each concept is shown in Table 3.

Although the data do not support our hypothesis, we are encouraged by the data. The difference in achievement on two of the concrete concepts, MIB and metal, is small and the level of achievement is high for both concrete and formal students. Statistical tests show no significant difference in achievement between concrete and formal operational students on the metal concept. However, the difference on the MIB and acid-base (operational) concepts was statistically significant. However, difficulties that occurred when the acid-base concept was taught lead us to place less faith in that result.

All of the lessons were taught during a 20 minute activity period and the test over the lesson was administered during the same period. In the lesson over acid and base (operational), the student had to test a number of solutions with litmus, check their conductivity, and see if there was a reaction with zinc which would produce hydrogen gas. The concrete operational students were less organized than the formal operational students and several of them were rushed to finish the activity. It is quite possible that the result on this lesson was due to factors other than difference in intellectual development. It is also possible that experimental aspects of the lesson required formal thought. We are not sure at this time.

What we are sure about is that the difference in achievement between concrete and formal operational students is less when they study concrete concepts than when they study formal concepts. Isomer, ideal gas, and the Brönsted-Lowry concept of acid and base are all concepts that lack perceptible instances, perceptible attributes, or both. They are formal concepts. The difference in achievement on these formal concepts was about double the difference in achievement on the concrete concepts.

The significance of this study is that it suggests that it may be possible to use Piaget's theory to identify concepts which are likely to be difficult for concrete operational students to learn. Knowing this, we may be able to restructure our courses so that these concepts are at least postponed until students have developed a vocabulary and some basic skills that may make these concepts more accessible.

We are, of course, anxious to learn how we can make formal concepts understandable to students. One aspect of the study that I have described touches on this question.

I have suggested that many concepts are difficult because they lack perceptible instances or perceptible attributes or both. Ideal gas is just such a concept. It is, if you will, a figment of our imagination. How can we make it real to students? One strategy is to use what I have called "pseudo-examples." We show small BB's bouncing about in some kind of random fashion; we show what happens when we apply pressure to this system of BB's; we draw illustrations of BB's that are essentially point masses and show what we think would happen when the pressure becomes very great. These are not illustrations that we are giving. They are not real examples of the behavior of an ideal gas. They are, I suppose, a kind of analogy. However, they are analogies that closely mimic the real thing. They are analogies like those often used in mathematics -- a dot on a piece of paper to represent a point, a mark on a sheet of paper to represent a line, a figure made by connecting three of these "lines" to represent a triangle. These representations are <u>not</u> the same as the concept being taught but they come so close that few students ever realize that they are <u>not</u> actual examples of the concept.

In this study we first taught the concept of an ideal gas using line drawings to illustrate the behavior of an ideal gas and to contrast its behavior with that of a real gas. Concrete operational students who studied this lesson averaged 61% on the test following the lesson and formal operational students averaged 72%. We then taught the same lesson to another group of students but left out the illustrations. In this case, the mean for the concrete operational students was 51% and the mean for the formal students was 66%. It should be noted that the use of pseudo-examples improved the performance of both formal and concrete operational students but the effect seems to be slightly greater for the concrete operational students. This may not always be the case. Sheehan found that when he improved instructional materials, formal operational students benefited more than concrete operational students (7).

This study is exploratory and it would be dangerous to generalize from these results to classroom practice until other research has been carried out. Still, we are encouraged to believe that continued research along these lines may lead to guidelines for teaching concrete operational students which will lead to substantial improvements in their understanding of chemistry.

The last point that I would like to discuss is something for which I may be to blame. In the article on "Piaget for Chemists," I suggested that there may be some students at the concrete operational level who should be left there; that the effort required to get them to operate at the formal level may be more than we or they are willing to expend and that the chemical facts that they need to know may be such that they could be taught at the concrete level.

Since writing "Piaget for Chemists" I have talked to several teachers -- mostly high school teachers -- who have reasoned that since 50% or more of their students are likely to operate at the concrete operational level, they should design their course so that there is no need for formal operational thought. After all, it isn't fair to ask students to do something that they are not capable of doing.

Even though I do believe that there may be circumstances in which one should design the course to minimize the need for formal thought, this reasoning frightens me. It seems to me to be a little like a basketball coach noting that his new team members aren't very good at dribbling or passing and deciding that he should design his training program so that there is never any need for the players to dribble or pass. In that way they can all be successful and happy. Unfortunately, the game isn't basketball without passing and dribbling and the course isn't science if we never use abstractions, never think in terms of possibilities, never recognize the logical necessity of "all other things being equal", never learn to use proportional reasoning, and all of the other logical processes associated with formal thought.

I have little faith that a person will learn to dribble or pass if he is never asked to dribble or pass; likewise, I see little reason to believe that a person will develop the logic associated with formal operational thought if he is never asked to use that logic. Still, one would not begin to teach a person to dribble or pass with some complex drill involving these skills put together in some intricate pattern. One simply must get the feel of the ball first; toss it from hand to hand, bounce it a few times, bounce it from one hand to another, and so forth. It will take time

and it will take practice and it will take encouragement. It seems to me that this applies to any development of a complex set of skills. It may, in addition, require maturation.

Few two year olds seem able to dribble even after much practice. Few students below the age of 12 seem able to use formal thought even after much practice. It seems to me that, rather than try to eliminate the need for formal thought, we need to design our curricula so that there are many opportunities for students to use formal thought. These opportunities should be interspersed with a lot of concrete experience and the concrete experience should support those activities that require formal thought. We should design the curriculum so that we return frequently to the same kind of formal operational thought in new contexts and we should constantly encourage the student's faltering efforts.

I don't think that we know how to do what I am suggesting. We need a great deal of research on this question in order to learn the mix of formal and concrete activities to be included in courses. We need research to tell us strategies that will help students develop the skills inherent in formal operational thought, just as the coach needs to know drills that help players develop dribbling and passing skill. We need to know more about the number of students who will be able, in a reasonable length of time, to develop those skills to the level expected of "championship performance" and the number who will develop the skills only to the level need for "avocational activities."

Even though we have much to learn about how to promote intellectual development, several people have been working toward that end for several years and reports of their work provide a point of departure for additional

work in chemistry. Articles in the list of references by Arons, Bauman, Karplus, Renner, and Lawson as well as the ADAPT Report (19-31) describe efforts that appear to be producing some gains in intellectual development even though the results are not spectacular and the effort required on the part of student and teacher is sometimes substantial.

We have a long way to go before we know how to teach chemistry so that it is understood by all students. Piaget's theory provides a framework for understanding the difficulties that some students have. If it does not eventually show us how to lead students to the promised land of understanding, it can at least give comfort to those in the hell of ignorance, confusion, and frustration.

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Table 1 †

Cell Means and Standard Deviations for Achievement Tests

Treatment Group*	N	Unit II	Unit III	Unit IV	Unit V	Achiev.	Retention
Lecture	41	8.95 (1.43)	8.49 (1.38)	7.76 (2.09)	7.90 (1.94)	39.44 (6.42)	41.74 (6.25)
Concrete	28	9.14 (1.20)	8.53 (1.40)	7.85 (2.35)	7.67 (2.12)	39.46 (5.65)	42.69 (4.95)
Formal	13	8.53 (1.81)	8.38 (1.38)	7.54 (1.45)	8.38 (1.44)	39.38 (8.09)	39.69 (8.27)
Laboratory	48	9.14 (1.03)	9.04 (1.35)	7.08 (2.53)	7.26 (2.78)	39.94 (6.95)	40.91 (9.34)
Concrete	28	8.85 (1.78)	8.64 (1.54)	6.39 (2.89)	7.17 (2.80)	37.57 (7.82)	39.05 (11.28)
Formal	20	9.55 (.60)	9.60 (.75)	8.05 (1.50)	7.35 (2.83)	43.25 (3.58)	43.50 (4.79)

*A score of 3 or less out of 8 on the Formal Reasoning Test was used to classify subjects as concrete.

A summary of the analysis of variance for each achievement test is given in Table 2.

† Table taken from Kulm, 1977.

Table 2 †

Analysis of Variance Summary for Achievement Tests

Source	df	Unit II	Unit III	Unit IV	Unit V	Achieve	Retention
Treatment	1	.50	3.15	2.37	1.74	.02	.32
Cog. Level	1	.25	2.14	2.54	.55	5.02**	.49
Interaction	1	5.86**	3.48	3.77*	.24	4.01*	4.44*
Residual	85						

*$p < .05$

**$p < .025$

† Table taken from Kulm, 1977.

Table 3

Means and Mean Percents for Achievement Tests

	Concrete Concepts		
Group	MIB	Metal	Acid-Base (operational)
Concrete	$\bar{X}$ 21.20	19.33	15.80
	% 85	81	66
Formal	$\bar{X}$ 23.05	20.88	20.08
	% 92	87	84

	Formal Concepts			
Group	Ideal Gas (examples)	Ideal Gas (no examples)	Isomer	Acid-Base (Bronsted-Lowry)
Concrete	$\bar{X}$ 14.75	12.15	12.08	13.33
	% 61	51	60	37
Formal	$\bar{X}$ 17.31	15.92	16.29	19.75
	% 72	66	81	55

Unit II Numeration Systems Lab II-1

Objectives:

Write expanded numerals for
a. decimal base numerals
b. non-decimal base numerals

Materials: Multibase blocks: base 6, 10

Procedures:

A. For the following explorations, use base 6 wood.

1. Determine the number of:
   a. Units required to form one long, _____.
   b. Units required to form one flat, _____; longs required to form one flat, _____.
   c. Units required to form one block, _____; longs required to form one block, _____.
2. Count out 17 units. By means of trading (units for longs, longs for flats, etc.) express 17 in terms of the fewest number of pieces of wood. How many blocks, flats, longs and units did you use? _____ blocks, _____ flats, _____ longs, _____ units.
3. Follow the same procedure as in Question 2 for:
   a. 24 units = _____ blocks, _____ flats, _____ longs, _____ units.
   b. 57 units = _____ blocks, _____ flats, _____ longs, _____ units.
   c. 143 units = _____ blocks, _____ flats, _____ longs, _____ units.
   d. 746 units = _____ blocks, _____ flats, _____ longs, _____ units.
4. Give a general rule for trading units for longs, longs for flats, or flats for blocks, in base 6. _____
   _____
5. What base 6 numbers can be expressed in terms of *only*:
   a. Units? _____
   b. Longs? _____
   c. Flats? _____
   d. Blocks? _____

6. What base 6 numbers can be expressed in terms of:
   a. Longs and units only (at least one of each)? _____
   b. Flats and longs only? _____
   c. Flats, longs and units? _____
   d. Blocks and units? _____
   e. Blocks and longs? _____
   f. Blocks, longs and units? _____
   g. Blocks and flats? _____
   h. Blocks, flats and units? _____
   i. Blocks, flats and longs? _____
   j. Blocks, flats, longs and units? _____
7. What is the largest base 6 number which can be expressed in terms of units only (that is, before trading must occur)? _____ Longs only? _____ Flats only? _____ Blocks only? _____
8. Answer Question 7 for the smallest base 6 number:
   Units only? _____ Longs? _____ Flats? _____
   Blocks? _____

B. Using base 10 wood, answer Questions 1–8.

C. Generalize your answer to Questions 1, 4, 5, 6, 7 and 8 for any base b wood.

Appendix B

MATH 130

Unit II Test

Choose the <u>one</u> best answer to each of the following.

1. Which item represents 520143_6 in expanded notation?
   (a) $5x10^5 + 2x10^4 + 0x10^3 + 1x10^2 + 4x10^1 + 3x10^0$
   (b) $5x6^6 + 2x6^5 + 0x6^4 + 1x6^3 + 4x6^2 + 3x6^1$
   (c) $5x6^5 + 2x6^4 + 0x6^3 + 1x6^2 + 4x6^1 + 3x6^0$
   (d) $5x10^6 + 2x10^5 + 0x10^4 + 1x10^3 + 4x10^2 + 3x10^1$
   (e) None of the above

2. Which item represents $3x10^3 + 2x10^2 + 8x10^1 + 5x10^0 + 2x10^{-1} + 4x10^{-2}$ in standard notation?
   (a) 3285.24
   (b) 32850.24
   (c) 328.524
   (d) 3285.024
   (e) None of the above

3. Which of the following is equal to 142_5?
   (a) 1112_3
   (b) 66_7
   (c) 232_4
   (d) 55_8
   (e) 115_6

4. Choose the item which represents 123_{10} as a base seven (7) numeral.
   (a) 234_7
   (b) 324_7
   (c) 221_7
   (d) 432_7
   (e) 232_7

5. Choose the item which represents 248_{10} as a base four (4) numeral.
   (a) 332_4
   (b) 3123_4
   (c) 3320_4
   (d) 233_4
   (e) None of the above

6. Choose the item which is the correct answer for the multiplication problem in base 5.
   (a) 1131_5
   (b) 2030_5
   (c) 1031_5
   (d) 2131_5
   (e) None of the above

$$\begin{array}{r} 342_5 \\ \times\ 3_5 \\ \hline \end{array}$$

7. Choose the item which is the correct answer for the addition problem in base 7.
   (a) 2151_7
   (b) 1151_7
   (c) 1121_7
   (d) 1051_7
   (e) None of the above

$$\begin{array}{r} 256_7 \\ +562_7 \\ \hline \end{array}$$

8. Choose the item which is the correct answer for the subtraction problem in base 6.
   (a) 435_6
   (b) 423_6
   (c) 444_6
   (d) 434_6
   (e) None of the above

$$\begin{array}{r} 512_6 \\ -34_6 \\ \hline \end{array}$$

9. Construct a base six (6) addition table.

10. Construct a base three (3) multiplication table.